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Final Report for AOARD Grant AOARD-134092

“Development of Mid-infrared GeSn Light Emitting Diodes on a Silicon Substrate”

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Abstract:

The objective of the project is to develop (a) direct-bandgap Sn-based group-IV material with very low defect densities that meets the requirement for the device application and (b) a new type of Sn-based group-IV light-emitting diode (LED)–planar structure. In this period, we have progressed toward the milestones described in the proposal. The technical tasks of the project have nearly been completed, and we are proceeding to the tasks of next stage. On completing the goals, we have demonstrated (a) thick GeSn film with a defect densities $\sim 10^5/\text{cm}^2$, which we believe to be the lowest as reported in the literature (b) a planar LED, which is a new type of LED that exhibits better performance than conventional vertical LEDs. In the next stage, we will proceed to the fabrication and design of the planar system with both emitter and photodetector on a single chip.

This report is divided into the following three sections:

- (a) Material growth aimed at the minimization of defects and Structure design
- (b) A new type of light-emitting diode: planar GeSn-based light emitting diode
- (c) Related Publications

(a) Material growth aimed at the minimization of defects and Structure design

For the material growth, in addition to the conventional P-i-N diode structure, different heterostructures have been designed. The P-i-N device consists of: (a) a N-type doped Ge layer, (b) an undoped Ge/GeSn/Ge active layer, and (c) a P-type doped Ge layer. The design was aimed at reducing the defect density in the active i-layer; hence, a low dark current was obtained. The designed structures were grown on Ge-buffer Si (001) wafers using molecular beam epitaxy (MBE) with the low-temperature growth technique. (The Ge-buffer is so-called Ge virtual substrate. For a detailed description of these techniques, see “Investigation of Ge_{1-x}Sn_x/Ge with high Sn composition grown at low-temperature,” I. S. Yu, T. H. Wu, K. Y. Wu, H. H. Cheng, V. I. Mashanov, A. I. Nikiforov, O. P. Pchelyakov, and X. S. Wu, AIP ADVANCES **1**, 042118 (2011).) The defect densities of the samples were characterized through high-resolution X-ray measurement (XRD). The full width at half maximum (FWHM) of the active i-layer ranged from 200 arcsec to 500 arcsec, corresponding to defect densities ranging from $\sim 10^6 \text{ cm}^{-2}$ to $\sim 10^8 \text{ cm}^{-2}$. The optimized structure has a defect density approximately one order of magnitude smaller than those of our previous work (and other reports in the literature).

After the designing and optimization of the P-i-N diode which is grown on Ge-buffer Si wafer, we like to point out that, part of the defects in the active GeSn layer is originated from the “extension” of the threading dislocations generated at Ge/Si interface as shown by the cross-sectional transmission electron microscopy (XTEM) analysis. (The bulk lattice constants of the two materials are $a_{\text{Ge}} = 5.6573 \text{ \AA}$ and $a_{\text{Si}} = 5.4310 \text{ \AA}$, giving a lattice mismatch of $\sim 4.2\%$.) To remove those defects generated at Ge/Si interface, we proceed to develop P-i-N diode grown on Ge wafer. Different growth techniques are developed aiming to further reduce the defect densities in the active GeSn layer. Systematic investigation using different growth temperatures is performed. These samples are characterized by different techniques such as XTEM etc.. In regarding to the defect densities, here we show the results of XRD (both (004) scan and (224) reciprocal space mappings (RSMs) is performed). Fig. 1 shows a typical image of (224) RSMs and a (004) scan trace. The Ge and GeSn trace is marked by solid and dashed lines. From an analysis, the physical properties of the active GeSn layer (such as composition, strain etc.) is established. For the defect densities in the GeSn layer, estimated from the FWHM of the (224) RSMs, it is found to be less than $\sim 10^5/\text{cm}^2$ which we believe that this is the lowest value reported in the literature (reference 1 and reference within). This value is also well within the levels considered acceptable for device application. (We are writing up a paper on this result.) The predominant defects accommodating the lattice misfit between GeSn/Ge are edge

dislocations at the interface, which are parallel to the interface plane and should not degrade electrical properties and device performance.

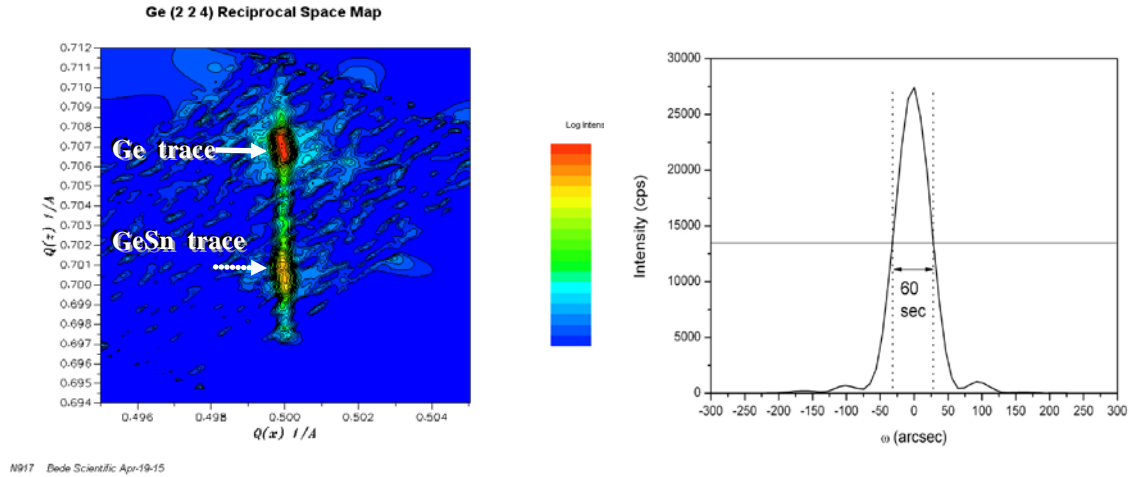


Figure. 1. Sample characterization (Left plot) (224) reciprocal space maps. (Right plot) Spectrum of (004) ω -2 θ measurements giving the full width at half maximum (FWHM) of 60 arcsec of the active i-layer

(b) A new type of LED: planar GeSn-based LED

In our previous work, the first of Sn-based group IV LED characterized by direct emission is demonstrated. The LED consists of P-i-N diode grown on Ge-buffer Si (001) wafer. By applying a voltage, light emits from surface (so-called vertical device) as illustrated in fig 2. The performance of the LED (emission intensity) at a specific wavelength depends on the thickness of the active layer, in addition to other factors (reference 2).

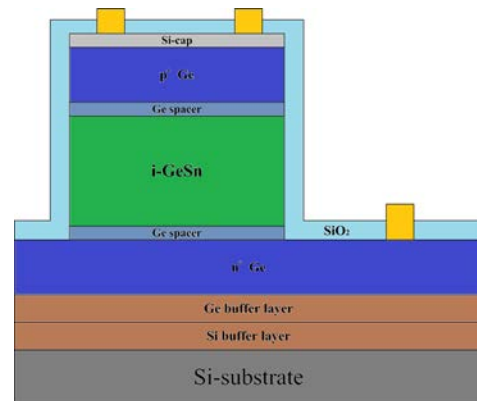


Figure. 2 Schematics of (a) cross section on view of the Ge/Ge_{0.922}Sn_{0.078}/Ge D H p-i-n diode grown on top of a Ge buffer layer on Si substrate.

Here, a new type of LED, the planar LED, is proposed and demonstrated. A schematic

plot of the planar LED is shown in Fig. 3(a). The structure consists of a undoped GeSn layer grown on Ge wafer. The sample is processed as a long strip using standard technique. Ion implantation is employed to fabricate n- and p-type GeSn at two ends of the strip for electrical contact. (The P-i-N lies in the plane of the Ge wafer.) By applying external voltage, instead of emitting light from the surface of the sample, the planar LED emits the light from the side of the strip (light parallel to the surface cf fig. 3(a)). Planar structures with different dimensions have been fabricated. Fig. 2(b) shows a typical emission spectrum operated at moderated applied voltage. (This is demonstrated for the first time in the literature and we are writing up a paper.) The electro-luminescence peak energy locates at mid-infrared region of ~ 0.6 eV corresponding to direct optical transition originated from the GeSn layer. Theoretical simulation on the optical properties is under investigated.

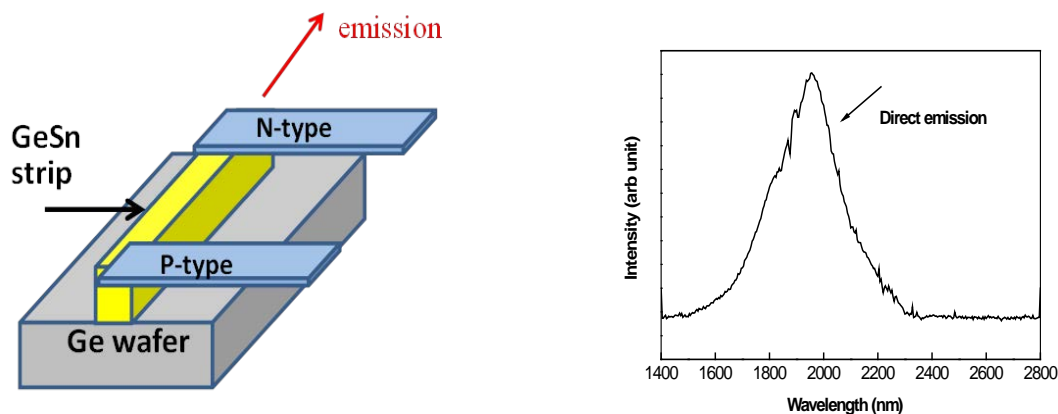


Fig. 3. (a) Left plot: Schematic plot of the proposed waveguided LED. (b) Right plot: EL spectrum

We like to point out that, the planar LED has the following advantages over the vertical LED: (a) As the length of the strip can be much greater than the thickness of the layer, the emission strength of the LED would be greater, resulting in a greater emission intensity as compared to the vertical LED. (b) The strip also functions as an optical cavity. (c) The structure can be integrated with most planar electronic devices, which is required for the integration of optoelectronic applications. With those advantages described above, in the next stage, we move to the laser structure which is desired in various applications.

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